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Sensor Technology Baseline Study for Enabling Condition Based Maintenance Plus in Army Ground Vehicles

by Muthuvel Murugan and Dy Le

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14. ABSTRACT This report documents the study of baseline sensor technology for enabling condition based maintenance plus in Army ground vehicles. The sensor study was driven from Failure Mode Effects Analysis (FMEA) conducted on four high cost driver components in Army ground vehicles by Tank Automotive Research, Development and Engineering Center (TARDEC). The four high cost driver components in Army ground vehicles as identified by TARDEC are engines, transmissions, batteries, and alternators. This report provides an assessment of current ground vehicle sensor systems and new baseline sensor technologies that may be used to support prognostic/diagnostic fault mode coverage including structural and component health monitoring for enabling condition based maintenance plus (CBM +) strategies to increase the operational availability of Army ground vehicles.						
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1. Summary

This report discusses the research conducted by the U.S. Army Research Laboratory, Vehicle Technology Directorate (ARL-VTD) on enabling condition based maintenance plus (CBM+) in military ground vehicles. The main tasks of this research, as planned to be accomplished over a span of 3 years, are given below:

- Conduct a sensor study driven from Tank Automotive Research, Development and Engineering Center (TARDEC) developed Failure Modes Effects Analysis (FMEA) to determine sensor technology baseline of four high cost driver components (engines, transmissions, batteries, and alternators) in coordination with the ARL, Sensors and Electron Devices Directorate (SEDD) 2010 Technology Program Agreement (TPA).
- Conduct performance root cause analysis to identify the source of performance degradation using component-level and platform-level seeded fault test data from TARDEC and U.S. Army Materiel Systems Analysis Activity (AMSAA). Physics of failure will be studied and documented to determine the actual mechanism causing the fault or performance degradation.
- Develop and validate methodology and algorithm for determining the remaining useful life of high pay-off components. Develop and demonstrate additional sensing and prognostic reasoning capabilities through design of experiments and seeded fault testing.

This report specifically covers the task conducted during the first year of research to determine baseline sensor technology based on TARDEC developed Failure Mode Effects Analysis of the high cost driver components of Army ground vehicles, such as engines, transmissions, batteries, and alternators.

2. Introduction

Condition Based Maintenance (CBM) of military vehicles is an important initiative from the Department of Defense (DoD) that aims at saving cost of operation and improves the safety of warfighters during missions. Instead of waiting for vehicle and equipment failure or typical scheduled maintenance intervals (Failure Based or Schedule Based Maintenance), CBM allows for real-time operational data to be transmitted seamlessly to the maintenance depot to assess the condition and health of various equipments. Using CBM strategies will ensure mission readiness with reduced down-times of Army vehicles/assets and automated just-in-time preventive maintenance.

The performance of military ground vehicle systems can degrade quickly due to severe operational usage and extreme harsh environments in theater. Current maintenance methods rely mostly on time based preventive maintenance schedules or maintenance triggered after detecting failure of components in vehicles. These methods are labor intensive and results in high operational cost. Through CBM, the vehicle reports system health, from tire pressure information to fuel consumption to ammunition levels, through the use of a Health and Usage Monitoring System (HUMS) similar to a health monitoring system used in aircraft. The main requirement for HUMS is a thorough understanding of the ways in which system condition is degenerated together with the ability to detect, identify, prognosticate anamolies, and communicate all conditions that require maintenance immediately. Thus, CBM strategies can greatly influence the safety of operation and readiness to successfully complete missions.

In this report, we study and analyze the Failure Mode Effects Analysis (FMEA) reports of high cost driver components, such as engines, transmissions, alternators, and batteries, in military ground vehicles generated by Tank Automotive Research, Development and Engineering Center (TARDEC). From this analysis, the common failure modes and mechanisms are identified. Based on this analysis, baselines sensor technologies are determined to prognosticate these types failure causes early, prior to actual break-downs, by continuously monitoring the states and condition of high cost driver components during operation.

3. Failure Mode Effects Analysis (FMEA)

The following four FMEA reports received from TARDEC were analyzed to determine various baseline sensor technologies that could be utilized to enable CBM+ in military ground vehicles.

FMEA report on C7 Caterpillar engine (*1*) received from TARDEC, was analyzed. This FMEA report contained information on failure modes, potential causes of failure, failure effects, and criticality assessments of engine components. The FMEA report on the engine was analyzed to come up with potential sensing technologies that could be used to enable health monitoring of engine and detect component failures in advance to increase the operational availability of this high cost driver in a military ground vehicle.

FMEA report on Allison transmission (*2*) received from TARDEC, was studied. This FMEA report contained similar information like engine system on potential failure modes, potential causes of failure, failure effects, failure detection method, and critically assessments. Analysis of the FMEA on transmission was conducted to come up with a recommendation on sensor technologies to address condition-based maintenance strategies. Another FMECA report conducted by a contractor, Global Technology Connection, Inc. (*3*) was also received from TARDEC. This study recommends a suite of sensors that can be added to enable CBM+ for Bradley transmissions. The findings in this report were analyzed and considered for determining suitable sensor technologies to enable condition monitoring of an automotive transmission, which is identified as one of the high cost drivers in military ground vehicles.

FMEA report on Generator (Alternator) for a military truck vehicle system, (*4*) received from TARDEC, was studied and analyzed. Recommended sensors to enable CBM plus for Army ground vehicle alternators are listed in the discussion on sensor technology baseline study (section 4 of this report).

FMEA report on lead acid battery used in several Army ground vehicles, (*5*) was studied and analyzed. Recommended sensors for battery health monitoring are listed in the discussion on sensor technology baseline study section of this report.

4. Discussion on Sensor Technology Baseline Study

4.1 Engine

FMEA report on Caterpillar Model C7 Diesel engine received from TARDEC was studied and analyzed. The engine is an in-line 6 cylinder (7.2 L), turbo-charged, Air to Air Aftercooler diesel engine, producing 330 hp as shown in figure 1. The FMEA report contained information on potential failure modes, potential causes of failure, failure effects, failure detection method, and criticality assessments. By studying and analyzing this report, an attempt has been made to identify all possible sensor technologies, which could enable engine system health monitoring. Table 1 provides a list of recommended sensor technologies to monitor and detect potential failure modes during in-service time to reduce potential engine down-time or non-availability.

Figure 1. Caterpillar C7 diesel engine.

Table 1. Sensor technology baseline study based on engine FMEA report.

Failure Mode	Potential Causes	Sensing Strategies	Baseline Sensor Technology
Oil in cylinder or unburnt fuel (blue exhaust smoke from engine)	Faulty engine oil level; Worn piston rings; Worn valve guides; Worn oil seals; Faulty cylinder head assembly	Oil level and temperature sensing; Engine vibration sensing; Exhaust smoke analysis	Oil level sensor; Oil temp sensor; Engine vib. sensor; Exhaust Gas Analyzer sensor
Reduced vehicle motive power (cannot reach vehicle speed limit)	Faulty fuel transfer pump; Faulty fuel filter (restricted); Faulty vent hose; Loss of compression; Degraded exhaust valve; Degraded turbocharger; Air cleaner restricted; Secondary fuel filter faulty (restricted); Faulty fuel lines	Fuel flow sensing along fuel lines before and after fuel filters; Air flow sensing after air cleaner	Fuel flow sensor; Air flow sensor
Engine cranks but does not start	Engine oil level low; Air cleaner faulty (restricted); Fuel transfer pump faulty; Fuel hose and/or fittings faulty; Fuel/water separator faulty; Crank and cam position sensor failure; Engine Control Unit (ECU) failure; Fuel tank faulty	Oil level sensing; Air flow sensing; Fuel contaminant sensing; Fuel pressure sensing in fuel tank; electrical disconnect sensing	Oil level sensor; Air flow sensor; Fuel contaminant sensor; Fuel pressure sensor; Current/voltage sensor across ECU to detect electrical disconnects
Engine does not crank	Batteries damaged; Air compressor faulty; Hydraulic pump faulty; Fuel injectors faulty; Cylinder head assembly faulty; Engine assembly faulty; Battery cable connections faulty; Starter (solenoid winding) failure;	Current/voltage at battery terminal; Compressor air flow sensing; Hydraulic oil pressure/temperature sensing; Fuel pressure/flow sensing; Engine vibration sensing, Current/voltage sensing at starter terminals	Current/voltage sensor; Hydraulic oil pressure sensor; Hydraulic oil temp. sensor; Fuel pressure sensor; Fuel flow sensor; Engine vibration sensor
Engine misfires, runs rough, or is unstable	Cylinder(s) faulty; Charge air cooler faulty; Air cleaner element faulty; Air filter to turbocharger hose faulty; Engine Electronic Control Module ECM faulty; Engine oil level faulty; Fuel transfer pump faulty; Fuel filter faulty; Water in fuel/water separator; Vent hose faulty; Engine control harness faulty; Fuel lines faulty; Exhaust system faulty; muffler faulty; Exhaust tube faulty	Engine vibration sensing; Charge air temperature sensing; Air flow sensing after air cleaner element and air filter to turbocharger; Electrical disconnect sensing; Engine oil level sensing; Fuel flow sensing; Fuel contaminant sensing; Vent air flow sensing; Engine control harness electrical disconnect (and wire chafing) sensing; Exhaust air flow sensing; Exhaust gas analyzer sensing	Vibration sensor; Air temp. sensor; Air flow sensor; Current/voltage sensor to detect electrical Disconnects/wire chafing; Fuel flow sensor, Fuel contaminant sensor; Exhaust gas analyzer sensor

Table 1. Sensor technology baseline study based on engine FMEA report (continued).

Failure Mode	Potential Causes	Sensing Strategies	Baseline Sensor Technology
Engine overheats	Engine oil level faulty; Drive belt loose or damaged; Tension pulley loose or damaged; Cooling system failure (degraded/obstructed radiator, etc.)	Engine oil level sensing; Drive system pulley rpm sensing; Drive belt tension sensing; Coolant flow and temperature sensing; Coolant level sensing	Oil level sensor; Drive system Tachometer for pulleys; Coolant flow sensor; Coolant temp. sensor; Coolant level sensor
Engine overspeeds on start	Faulty fuel control linkage; Throttle position sensor failure	Fuel flow quantity sensing with time; Recording throttle position sensor current/voltage	Fuel flow sensor; Current/voltage sensor for throttle position sensor
Engine speed is not stable	Faulty valve clearance adjustments; Engine sensor failure	Engine vibration sensing; Engine oil temp. sensing; Current/voltage sensing for sensor	Engine vibration sensor; Engine oil temp. sensor; Current/voltage sensor
Engine stalls at low RPM	Primary and secondary fuel filters clogged; Unit injector(s) faulty; Air filter element restricted; Fuel pressure low; Injection actuation pressure faulty; Air in fuel system; Fuel pressure regulating valve faulty; Air cleaner needs service; Air particle extraction tube faulty; Air cleaner to turbocharger tube faulty; Fuel hoses damaged or leaking	Fuel pressure sensing; Air flow sensing; Fuel contaminant sensing, Current/voltage sensing for Fuel pressure regulating valve; Fuel flow sensing	Fuel pressure sensor; Fuel contaminant sensor; Current/voltage sensor for fuel regulating valve (and wire chafing); Fuel flow sensor
Fuel/air system problem (excessive black or gray exhaust smoke from engine)	Air filter faulty (air system fault); Unit injector faulty	Air flow sensor; Fuel pressure /and or flow sensing	Air flow sensor; Fuel pressure/flow sensor
Excessive engine oil consumption	Engine oil level faulty; Engine oil filter damaged; High pressure oil pump lines leaking; Valve cover or gasket faulty; Oil pressure switch leaking; Crankcase breather unserviceable; Oil pressure transmitter faulty; Cylinder compression low	Engine oil level sensing; Oil pressure/and or flow sensing; Engine vibration sensing; Electrical disconnect sensing at sensor terminals	Engine oil level sensor; Oil pressure/flow sensor; Vibration sensor; Current/voltage sensor at sensor terminals

Table 1. Sensor technology baseline study based on engine FMEA report (continued).

Failure Mode	Potential Causes	Sensing Strategies	Baseline Sensor Technology
Fuel in lubrication oil	Fuel transfer pump seal faulty; Unit injector faulty; Excessive idling; Cylinder compression low; Cylinder head assembly faulty	Fuel pressure sensing at pump/unit injector; Cylinder pressure/temperature sensing	Fuel pressure sensor; Cylinder pressure and temperature sensor
Intermittent engine shutdowns, low power, or power cut-outs	Fuel transfer pump faulty; Engine oil filter faulty; Engine oil level faulty; Fuel filter faulty; Vent hose faulty; Engine control harness connector P2 faulty; Fuel lines faulty; Fuel/water separator faulty	Fuel pressure sensing; Engine oil pressure /and or flow sensing; Engine oil level sensing; Wire harness electrical disconnect sensing; fuel contaminant sensing	Fuel pressure sensor; Fuel flow sensor; Engine oil level sensor; Wire harness current/voltage sensor; Fuel contaminant sensor
Excessive engine vibration	Air filter element faulty; Vibration damper bolts missing, loose or damaged; Toe-in out of adjustment; Vibration damper faulty; Cylinder compression imbalances; Engine mounts faulty	Air flow sensing at air filter; Vibration sensing at damper, engine mounts, and cylinder heads	Air flow sensor; Vibration sensor
Water in the combustion chamber (heavy white exhaust smoke from engine, does not stop as engine reaches operating temperature)	Engine oil contaminated with coolant; Coolant contaminated with engine oil; Fuel hose(s) and or fitting(s) faulty; Fuel/water separator faulty; Contaminated fuel; Head gasket failure; Cracked engine block; Cracked cylinder head	Engine oil contaminant sensing; Fuel flow sensing; Fuel contaminant sensing; Engine vibration sensing; Engine cylinder temp. sensing	Engine oil contaminant sensor; Fuel flow sensor; Fuel contaminant sensor; Engine vibration sensor; Engine cylinder temp. sensor

4.2 Transmission

FMEA report on Allison 2500 SP Transmission, as shown in figure 2, used in typical Army ground vehicles was received from TARDEC. This report was studied and analyzed to come up with possible sensing strategies as listed in table 2.

Figure 2. Allison transmission 2500 SP.

Table 2. Sensor technology baseline study based on transmission FMEA report.

Failure Mode	Potential Causes	Sensing Strategies	Baseline Sensor Technology
Contaminated transmission lubrication	Internal transmission failure; Clogged filter; Excessive heat	Transmission fluid contaminant sensing; Fluid temp. sensing	Fluid contaminant sensor; Fluid temp. sensor
Engine excessively revs on full throttle up shifts	Internal transmission failure; Incorrect calibration; Incorrect fluid level; Erratic speed sensor signal	Current/voltage sensing at sensor terminals; Fluid level sensing	Current/voltage sensor measured at sensor terminals; Fluid level sensor
Excessive slippage and clutch chatter	Internal transmission failure; Faulty torque converter; Clutch pressure low; Fluid level low; Aerated fluid; Transmission control module incorrectly calibrated; Throttle position sensor failed; Incorrect fluid level; Worn clutch pack; Incorrect speed sensor	Fluid pressure sensing; Contaminant sensing; Electrical disconnect sensing at sensors, Fluid level sensing	Fluid pressure sensor; Contaminant sensor; Current/voltage sensor at terminals/wiring; Fluid level sensor
Excessive stationary vehicle creep in first and reverse gears	Internal transmission failure; Engine idle speed set too high	Fluid pressure and temperature sensing; Contaminant sensing; Analyze engine Prognostic Health Management (PHM)	Fluid pressure sensor; Temp. sensor; Contaminant sensor; Investigate engine PHM sensing

Table 2. Sensor technology baseline study based on transmission FMEA report (continued).

Failure Mode	Potential Causes	Sensing Strategies	Baseline Sensor Technology
Fluid leak at output shaft	Seal at output flange damaged; Worn output shaft bearing; Flange worn at seal surface	Fluid temp./pressure sensing; Contaminant sensing	Fluid temp./pressure sensor; Contaminant sensor
Fluid leaking from fluid filler tube and/or breather	Fluid contaminated with foreign liquid; Blocked breather; Incorrect fluid level; Dipstick loose or seal worn	Fluid contaminant sensing; Fluid level sensing	Fluid contaminant sensor; Fluid level sensor
Fluid leaks	Transmission input seals worn/damaged; Damaged gaskets; Blocked breather; Cracked casing; Loose fluid filler or drain plug; Worn output shaft bearing; Fluid level too high	Fluid level sensing; Fluid temp./pressure sensing	Fluid level sensor; Fluid temp./pressure sensor
Intermittent noise – buzzing (acoustic wave)	Low main pressure causes main regulator to oscillate; Internal transmission failure; Air leak in oil suction screen canister; Clogged filter; Transmission fluid level low; Incorrect sump filter installed; Faulty torque converter; Aerated fluid	Fluid level sensing; Fluid pressure sensing; Contaminant sensing	Fluid level sensor; Fluid pressure sensor; Contaminant sensor
Low lubrication pressure	Excessive internal fluid leakage; Converter relief valve sticking; Lubrication regulator valve sticking; Incorrect fluid level; Blocked suction filter; Cooler lines restricted or leaking; Faulty pump	Fluid level sensing; Oil pressure sensing across pump; Pressure sensing in cooler lines	Fluid level sensor; pressure sensor
Low main pressure in all ranges	Internal transmission failure; Incorrect fluid level; Faulty pump; Blocked suction filter	Fluid level sensing; pressure sensing across pump and suction filter	Fluid level sensor; pressure sensor

Table 2. Sensor technology baseline study based on transmission FMEA report (continued).

Failure Mode	Potential Causes	Sensing Strategies	Baseline Sensor Technology
Low main pressure in specific ranges, normal pressure in other ranges	Internal transmission failure; Faulty pump	Fluid pressure sensing across pump	Fluid pressure sensor
Low stall speeds	Engine not performing efficiently due to blocked injectors, dirty air filter, throttle linkage problem etc.	Examine sensing for engine PHM	Integrate appropriate engine PHM sensors
No transmission control module light at ignition	Incorrect wiring to and from transmission control module; faulty light bulb; Transmission control module connected to battery power instead of ignition power	Current/voltage sensing for control module wire harness	Current/voltage sensor
Overheating in all ranges	Cooler flow loss due to internal transmission leakage; Engine overheating; Fluid cooler lines restricted; Air flow to cooler obstructed; Incorrect fluid level; Aerated fluid	Fluid temp. sensing; Fluid pressure sensing; Air flow to cooler pressure sensing; Fluid level sensing; Contaminant sensing	Fluid temp./pressure sensor; Air flow pressure sensor; Fluid level sensor; Contaminant sensor
Shudder when shifting into forward or reverse	Internal transmission failure	Fluid level sensing; Fluid temp./pressure sensing; Contaminant sensing	Fluid level sensor; Fluid temp./pressure sensor; Contaminant sensor
Transmission control module light flashes intermittently	Loose wire to transmission control module light, Faulty vehicle wiring; Faulty ground connection	Current/voltage sensing on wiring harness	Current/voltage sensor for wire harness (wire chafing)
Transmission control module light will not extinguish after engine has started	Faulty transmission control module light relay; Faulty transmission control module; Faulty harness	Current/voltage sensing on wiring harness	Current/voltage sensor for wire harness (wire chafing)

Table 2. Sensor technology baseline study based on transmission FMEA report (continued).

Failure Mode	Potential Causes	Sensing Strategies	Baseline Sensor Technology
Transmission does not shift properly (rough shifts, shifts occurring at too low or too high speeds	Sticking valves in control valve body; Leaking trim solenoids; Low main pressure; Faulty speed sensor/circuit; Loose or damaged speed gear; Faulty throttle sensor/circuit; Incorrectly calibrated electronic speedometer; Incorrect fluid level; Contaminated fluid; Engine idle speed too fast	Fluid level sensing; Fluid temp./pressure sensing; Current/voltage sensing for possible electrical disconnects at sensors and on wire harness	Fluid level sensor; Fluid temp./pressure sensor; Current/voltage sensor at sensor terminal and on wiring harness (wire chafing)
Transmission will not make a specific shift	Extreme fluid temperature; Low engine power; Incorrect shift calibration; Faulty speed sensor/circuit; Faulty temperature sensor/circuit	Fluid temp. sensing; Current/voltage sensing for sensors and wiring harness	Fluid temp. sensor; Current/voltage sensor (wire chafing)
Transmission will not select	Low hydraulic pressure; Throttle position sensor or linkage not functioning properly; Faulty speed sensor; Faulty wiring in transmission control module	Fluid pressure sensing; Fluid level sensing; Current/voltage sensing for sensors and wiring harness	Fluid pressure sensor; Fluid level sensor; Current/voltage sensor (wire chafing)
Transmission will not stay in forward or reverse	Faulty solenoid; Low hydraulic pressure; Control main filter clogged; Transmission fluid level low	Fluid pressure sensing; Fluid level sensing; Current/voltage sensing at solenoid	Fluid pressure sensor; Fluid level sensor; Current/voltage sensor

FMECA study report (*3*) on military ground vehicle transmission was also received from TARDEC. This study was performed by a contractor, Global Technology Connection, Inc. This study recommends additional sensors to enhance the diagnostic/prognostic capability. The study suggests that a predictive capability could be enabled for the transmission by adding accelerometers and/or a torque sensor with additional hardware and software to conduct broad band vibration analysis for the health monitoring of mechanical components and for lubrication faults. Also, temperature sensors can be added to monitor the transmission fluid temperature and coolant temperature, which will be useful for predicting the transmission fluid life. In addition, oil contaminant and/or viscosity sensors could be implemented to enable coverage for additional lubrication related failure modes.

4.3 Alternator

FMEA study report (*4*) performed by Camber Corporation on Generator (Alternator) for military ground vehicles (see figures 3 and 4), was received from TARDEC. This study reports that the greatest number of failures in alternators involve variations in voltage and current, internal failures, and damage from burning. The report suggests that the overwhelming majority of generator replacements are a result of either burnt/charred internal components or other internal failures that result in incorrect voltage or current output. The potential failure modes and the underlying causes of failure as they relate to the generator (alternator) with possible sensing strategies and sensor recommendations are listed in table 3 below.

Figure 3. Generator (alternator) for a military ground vehicle.

Figure 4. Side view of a military ground vehicle (generator inside engine compartment).

Table 3. Sensor technology baseline study based on alternator FMEA report.

Failure Mode	Potential Causes	Sensing Strategies	Baseline Sensor Technology
Burned up stator/winding failure	Failed or under-charged battery causes excessive draw on the generator as it attempts to run all the accessories and recharge the battery simultaneously; Wire insulation sheath damage caused by accessories drawing more current than the electrical system design capacity	Detecting amperage (current) draw on alternator that is above specified maximum; Detecting increased resistance at connector studs; Wire chafing resistance sensor on wiring harness	Current sensor to monitor amperage exceedance; Resistance measurement sensor (wire chafing)
Regulator failure	Slave cable is not removed after the slaved vehicle is successfully jump-started, causing the regulator and other internal components to experience a current overload; Extreme heat, vibrations, and electrical shorts cause solid state components to fail, inhibiting the regulator's ability to adjust the rotor field's current	Current sensing; resistance sensing; vibration sensing	Current/voltage sensor; Resistance sensor; Vibration (accelerometer) sensor
Connector failure (all terminals)	Corrosion, backed-off nuts, and/or bent studs prevent proper connection between the alternator and other electrical components, increasing resistance to current flow	Resistance sensing	Resistance sensor at studs
Internal failure of components with non-free spinning bearing	Foreign object debris (FOD) infiltrates generator housing and bearing, adding increased wear and heat to the bearing and causing galling and premature failure; Generator belts are too lose/tight causing increased wear of the bearing due to slight misalignment	Vibration sensing to monitor bearings.	Vibration sensor

4.4 Battery

FMEA study report (*5*) performed by Camber Corporation on lead acid battery, used in Army ground vehicles (see figure 5 below), was received from TARDEC. The report shows that based on the compiled statistical data, the greatest number of failure codes indicates an incorrect voltage output. The potential failure modes and the underlying causes of failure for the military ground vehicle battery with possible sensing strategies and sensor recommendations are listed in table 4 below.

Figure 5. Lead acid battery for Army ground vehicle.

Table 4. Sensor technology baseline study based on Hawker battery FMEA report.

Failure Mode	Potential Causes	Sensing Strategies	Baseline Sensor Technology
Battery cannot be connected to electrical system	Damage caused during shipping (mishandling) and stacking	Check battery state of charge before installation	Battery State of Charge Sensor (Two types are available): (a) Impedance spectroscopy and Coulomb counting: This multi-technology advanced sensor utilizes embedded impedance spectroscopy (EIS) technology and a coulomb counting technology to monitor state of charge of batteries. Coulomb counting technology provides the ability to measure the amount of current that is being drawn from the battery and the amount of current that flows back into the battery during recharge. This technology is currently used for mobile devices such as cellular phones and laptop computers; (b) Conductance technology: This technology measures the cold cranking amps (CCA) of the battery.
Battery has insufficient voltage output	Charging system failure, such as under/overcharging, regulator failures, dehydration, alternator failure, or wiring failure; Parasitic draw can reduce the efficiency of charging the battery and leads to the battery losing its charge when the engine is turned off; Extreme heat can cause excessive overcharging (gassing) or venting of hydrogen gas, which can render the battery inoperable; Plate corrosion is a normal consequence of charging and discharging in lead acid batteries. This can cause the battery to fail.	Monitor battery state of charge	Same as above. In addition, an infrared thermograph can be used to measure the heat on surface of the batteries. Also corrosion sensor can be used.

Table 4. Sensor technology baseline study based on Hawker battery FMEA report (continued).

Failure Mode	Potential Causes	Sensing Strategies	Baseline Sensor Technology
Battery inoperable (no charge, or cannot be charged)	Age is a factor. Uncontrolled storage and the passage of time reduce the charging capacity of the battery; Internal electrical failure caused by the mechanical failure of the internal battery construction; Battery explosion can be caused by excessive overcharging, venting gas with an external ignition source or thermal exposure; Physical damage such as impact damage on the battery case	Same as above	Same as above including a thermal infrared sensor to warn excessive heating.
Battery functional but usability is reduced	Optimal charging rate is a factor in battery failure, as batteries with different chemistry can require different charging voltages or charging cycles	Same as above	Same as above

The above list of possible baseline sensor technologies based on the FMEA reports of the four high cost driver components, such as engines, transmissions, alternators, and batteries, will need to be reviewed for redundancy and optimization with available sensing and monitoring using vehicle Controller Area Network (CAN) bus for a given vehicle architecture. The data acquisition frequency rates may need to be modified/adjusted for the various sensors to collect minimal and meaningful data to enable effective prognostics health monitoring. Also, a detailed cost-benefit analysis needs to be conducted for every additional sensor that may be necessary.

5. Conclusions

Sensing strategies and applicable sensor technology study to determine baseline of prognostic/diagnostic failure mode coverage have been conducted based on the FMEA reports received from TARDEC on the four high cost driver components, such as engines, transmissions, alternators, and batteries. This sensor study is intended to determine baseline of prognostics/diagnostics failure mode coverage and does not take into account existing sensors that feed specific component health data into the subject vehicle's CAN bus architecture. It is recommended that the overall sensor selection for CBM integration in a specific Army ground vehicle platform should consider a number of key factors such as sensor redundancy, sensor optimization, cost-benefit analysis or return-on-investment analysis for each added sensor in the vehicle and the associated hardware/software expenditure.

6. Future Recommendations

The following future work on this research will further advance the development of prognostic and diagnostic technologies that can be implemented in Army ground vehicles.

- Conduct performance root cause analysis to identify the source of performance degradation using component-level and platform-level seeded fault test data from TARDEC and AMSAA. Physics of failure need to be studied and documented to determine the actual mechanism causing the fault or performance degradation.
- Develop and validate methodology and algorithm for determining the remaining useful life of high pay-off components. Develop and demonstrate additional sensing and prognostic reasoning capabilities through design of experiments and seeded fault testing.

7. References

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List of Symbols, Abbreviations, and Acronyms

AMSAA	U.S. Army Materiel Systems Analysis Activity
ARL	U.S. Army Research Laboratory
CAN	Controller Area Network
CBM	Condition Based Maintenance
CBM+	condition based maintenance plus
CCA	Cold Cranking Amps
DoD	Department of Defense
ECU	Engine Control Unit
ECM	Electronic Control Module
EIS	Embedded Impedance Spectroscopy
FMEA	Failure Mode Effects Analysis
FMECA	Failure Mode Effects and Criticality Analysis
FOD	Foreign Object Debris
hp	horse power
HUMS	Health and Usage Monitoring System
L	Liter
PHM	Prognostic Health Management
RPM	Rotations Per Minute
SEDD	Sensors and Electron Devices Directorate
TARDEC	Tank Automotive Research, Development and Engineering Center
Temp. (temp.)	Temperature
TPA	Technology Program Agreement
VTD	Vehicle Technology Directorate
Vib. (vib.)	Vibration

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